CRYO-COOLED SAPPHIRE OSCILLATOR WITH ULTRA-HIGH STABILITY

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Abstract

We present test results and design details for the first short-term frequency standard to achieve ultra-high stability without the use of liquid helium. With refrigeration provided by a commercial cryocooler, the Compensated Sapphire Oscillator (10 K CSO) makes available the superior short-term stability and phase noise performance of cryogenic oscillators without periodic interruptions for cryogen replacement. Technical features of the 10 K CSO include use of a 2-stage cryocooler with vibration isolation by helium gas at atmospheric pressure, and a new sapphire/ruby resonator design giving compensated operation at 8-10K with $Q = 1 - 2 \times 10^9$. Stability of the first unit shows an Allan Deviation of $\sigma_y \leq 2.5 \times 10^{-15}$ for measuring times of 200 seconds $\leq \tau \leq 600$ seconds. We also present results showing the capability of the 10 K CSO to eliminate local oscillator degradation for atomic frequency standards. Configured as L.O. for the LITS-7 trapped mercury ion frequency standard, the CSO/LITS combination demonstrated a limiting performance of $3.0 \times 10^{-14}/\tau^{1/2}$, the lowest value measured to date for a passive atomic frequency standard, and virtually identical to the value calculated from photon statistics.

I. BACKGROUND

Cryogenic oscillators operating below about 10 K offer the highest possible short term stability of any frequency sources [1]-[3]. However, their use has so far been restricted to research environments due to the limited operating periods associated with liquid-helium cooling.

We have developed a cryogenic sapphire oscillator for ultra-high short term stability and low phase noise in support of the Cassini Ka- band Radio Science experiment [1]. With cooling provided by a commercial cryocooler instead of liquid helium, this standard is designed to operate continuously for periods of a year or more. Performance targets are a stability of 3×10^{-15} (1 second $\leq \tau \leq 100$ seconds) and a phase noise of -73 dBc/Hz @ 1Hz measured at 34 GHz. Installation of these oscillators in stations of NASA's Deep Space Network (DSN) is planned in the years 2000 to 2002.

Continuous long-term operation is crucial to the applicability of short-term frequency standards since they are typically are used to "clean up" the short-term variations of a longer term atomic standard, the combined output being then distributed to various users. Furthermore, the cryogenic oscillators can provide local oscillator (L.O.) performance as required by a new generation of passive atomic standards. These include the Cesium Fountain and Trapped Ion standards which are under development at many laboratories around the world, and whose potential is presently thwarted by the lack of available L.O. performance [4]-[6]. Continuous operation of the L.O. is crucial to the utility of these atomic standards.

Our development was enabled in part by a new generation of 2-stage Giffard- McMahon (GM) cryocoolers which allow operation at temperatures down to 4.2 K [7]. Previously, such temperatures could only be achieved by the use of an additional Joule Thompson expansion stage, with increased complication and cost, and with reduced reliability due to the likelihood of clogging the small expansion leak.

Any cryocooler generates vibrations which, if coupled to a high- Q electromagnetic resonator, would degrade its frequency stability. However, a technology has been developed that allows isolation of cryocooler vibrations from an experiment while providing adequate cooling. In the face of very stringent vibration requirements, the experimental Mössbauer community has successfully adopted a methodology that

transfers heat to cryocooler without physical contact by using turbulent convection in a gravitationally stratified helium gas [8].

Cryogenic standards have used both superconducting and sapphire resonators to achieve the $Q > 10^9$ required for 1×10^{-15} frequency stability. Superconducting resonator Q's degrade to unacceptable values above about 2K. However, Q's of a billion have been previously measured in whispering gallery sapphire resonators at temperatures up to 10 K [9], [10]. However, the temperature sensitivity of sapphire resonators is so large that high stability can only be attained near a preferred turn-over temperature where the slope of frequency vs temperature approaches zero. If sapphire turn-over temperatures could be raised from typical as-supplied values of 5 K- 6 K to a reproducible 8 K- 10 K, a practical cryo-cooled standard with 1×10^{-15} stability could be built.

The actual value of the turnover for any given resonator depends on the concentration of incidental ($\approx 1\mu g/g$ paramagnetic impurities as well as the properties of the electromagnetic mode that is being excited. If impurity levels could be accurately controlled it might be possible to construct resonators that would be compensated in the relatively narrow temperature band between that which can be achieved with available cryocooler cooling and the temperature at which the Q begins to degrade. However, a fairly large increase in impurity content is required because of a weak (fifth root) dependence of turn-over temperature on concentration [1]. And, this must be accomplished without degrading the resonator Q.

Sapphire resonators with external compensation have been demonstrated and proposed for high stability at cryogenic temperatures. A resonator with a mechanical compensation scheme demonstrated a stability of better than 1×10^{-13} at a temperature above 77 K [11], and combined sapphire rutile resonators have also been investigated [12]. However, the Q values of a million or so that are so far achievable with these schemes are far below those needed.

II. DESIGN ASPECTS

Cryogenic aspects of design are shown in Fig. 1 and have been presented previously [1]. The cryocooler is mounted as rigidly as possible to the floor and the cryostat assembly is independently supported from the floor using conventional vibration isolation components.

Cryogenic systems providing vibration- isolation by means of helium gas conduction are available commercially based on small 7 K 2-stage G-M cryocoolers. However, the available performance for these units is limited to temperatures above 13 K- 15 K, using a patented thermal design. Based on our calculations of thermal conduction by turbulent gas flow we conclude that a simple design with a gap of a few millimeters between concentric cylinders shows higher thermal conductivity for any given geometrical constraint than the patented designs [13].

The resonator design shown in Fig. 2 compensates the frequency variation of a whispering–gallery sapphire resonator by means of a proximate and thermally attached ruby element. The high chromium concentration in the ruby gives a large compensation effect that can be reduced by adjusting its position.

The ruby was constructed so as to allow assembly gaps of either 2 mm or 4 mm between ruby and sapphire elements.

A $WGE_{14,1,1}$ quasi-TE mode was chosen to minimize the size of the copper shielding container while still allowing a shield-limited Q of greater than 10^{10}. With significant axial H-fields, the WGE mode also facilitates coupling to a ruby element displaced axially from the sapphire. An operating frequency of 10.4 GHz was chosen to give effective spin-tuning without excessive losses. Finite element calculations were used to calculate energy in the ruby element and its diameter was adjusted to give the desired $\approx 0.12\%$ energy content [14].

Compensation design involves balancing the Debye expansion ($\propto T^4$) by a $1/T$ spin-dependent term. The sign of the spin term is appropriate for compensation for frequencies below the 11.44 GHz zero-field splitting. Microwave coupling to the spins depends on the geometry of the resonator and the electromagnetic mode–the WGE mode excited in the sapphire does not couple to the spins. This gives resonator baseline behavior without a temperature turnover, and thus avoids the variability of spin-tuning from sample to sample in even the best sapphire. A rotation of the magnetic field orientation from the vertical in the ruby is observable in Fig. 2 and provides effective coupling to the ruby spins.

Finally, ruby spin-tuning values are required to calculate the ruby electromagnetic energy requirement given above and the spin-loss values will place a limit on Q, and on the loss of Q with increasing turn-over temperature [15]. Our measurements of the characteristics of a 0.03 % g/g ruby sample are shown in Fig. 3 and have been confirmed with measurements of 5 more samples. For our operation 1 GHz below the zero-field splitting we calculate a spin-loss limiting Q of about 3×10^9.

III. EXPERIMENTAL

Fig. 4 shows the first reported frequency turnover for a resonator with adjustable compensation and ultra-high Q. The turnover temperature at 8.821 K for the first assembly is close to the calculated value of 7.25 K. The Q of the first sapphire was about 300 million at 8 K-10 K with or without the ruby compensating element. The mode excited is $WGE_{14,1,1}$ at 10.395 GHz.

Frequency stability tests were performed with and without the ruby compensation element. Even without compensation, the thermal ballast removes short-term variations, showing a random-walk type stability of approximately $3 \times 10^{-15} \times \tau^{1/2}$, observed for measuring times above about 30 seconds. Based on our thermal analysis, we expect the short-term behavior to improve as $1/\tau$ for measuring times longer than 0.8 seconds, the ruby-sapphire thermal response time. This would give a stability of less than 1×10^{-15} for measuring times $\tau \geq 10$ seconds.

Compensated stability tests with the first resonator assembly showed a flicker floor of about 7×10^{-15}. We have not yet determined if the floor was due to the somewhat low resonator Q or to an observed frequency pulling with RF amplitude of more than 1×10^{-11} Hz/Hz/dB.

Fig. 5 shows frequency stability measurements for the first resonator after it was sent back to the supplier

for an "after-polish anneal" which had been skipped on the first two samples in order to meet our delivery schedule. The resonator as assembled the second time shows an unloaded Q of about 1×10^9 with almost exactly critical coupling. Additionally, probably due to the better coupling, the resonator showed a sharply reduced RF amplitude pulling of $\approx 10^{-12}$ Hz/Hz/dB. The turnover temperature increased slightly to 8.54 K.

The short-term part of the stability shown in Fig. 5 is limited by maser performance with no additional fluctuations attributable to the CSO. The flicker floor is below $\sigma_y = 2.4 \times 10^{-15}$.

The low 10^{-13}/day drift of the CSO allowed easy application as an L.O. for the JPL Linear Ion Trap Standard (LITS) [4], [5]. Frequency pulling of $\delta\nu/\nu = 10^{-11}$ was possible by addition of an external DC voltage to the Pound frequency lock circuitry of the CSO. The LITS was tuned for high S/N and low $1/\tau^{1/2}$ fluctuations, yielding a calculated deviation for statistical (light count) variations of $3.0 \times 10^{-14}/\tau^{1/2}$.

Fig. 6 shows a comparison of the CSO–LITS standard with a SAO hydrogen maser. The measured stability is limited at all measuring times by hydrogen maser frequency fluctuations.

The significance of this demonstration is two-fold. First, use of the CSO as L.O. allows us for the first time to see the LITS stability essentially undegraded by L.O. effects [16]. Secondly, the coefficient of the $1/\tau^{1/2}$ slope is the lowest measured to date for a passive microwave atomic frequency standard, complementing previous demonstrations of exceptional stability of the LITS for measuring times of thousands of seconds to weeks and months [5].

IV. CONCLUSIONS

The 10 K Compensated Sapphire Oscillator has been demonstrated as the first continuously operable frequency standard with ultra-high short term stability. Phase noise tests are being addressed with construction of a second unit which should be operational within a few months. Stability is clearly superior to the hydrogen maser at short measuring times, and we expect to meet the requirement of $(3-4) \times 10^{-15}$ stability for 1 second $\leq \tau \leq 100$ seconds for the CASSINI Ka-band Experiment. Phase noise measurements are expected soon with the completion of a second unit.

Freed of the limitations of quartz or hydrogen maser L.O.'s the new generation of passive atomic standards such as the LITS and Cesium Fountain can now be operated continuously while realizing their inherent capabilities. A local oscillator with the capability of the 10 K CSO can enable these standards to achieve stabilities of better than $1 \times 10^{-14}/\tau^{1/2}$.

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Fig. 1. Cryogenic and vibration isolation systems showing measured temperatures. A small dewar fits closely around the cryocooler with the space between them filled with helium gas at atmospheric pressure.

Fig. 2. Compensated sapphire resonator showing details of electromagnetic and thermal design. The thin-walled stainless steel tube thermally isolates the resonator elements while providing good rf confinement. Electromagnetic field intensity varies approximately 1 order of magnitude per color band as calculated by the CYRES-2 finite-element computer program.

Fig. 3. Measured reactive and resistive components for the permittivity of 0.03 % ruby. Delta F is the frequency deviation from the 11.44 GHz zero field splitting for chromium impurities in ruby. Together, these two curves allow the spin-limited Q to be calculated for any ruby–sapphire compensated resonator. The dotted lines show slopes of -1 and +2 as predicted by the Lorenzian model.

Fig. 4. Measured temperature dependence of the compensated resonator with a 4 mm spacing between sapphire and ruby elements. This resonator shows a turn-over temperature of 8.821 K compared to the predicted value of 7.43 K shown in Fig. 2.

Fig. 5. Measured frequency stability for the 10 K CSO against a DSN-2 hydrogen maser tuned for best short-term stability. Even this "hot" H-maser reference dominates the observed short term variation. The long-term turn-up is due to the CSO and is likely caused by sensitivity of the rf electronics to room temperature variations.

Fig. 6. Comparison of the combined LITS / CSO to an SAO H-maser with excellent long-term stability. The LITS vs CSO data is obtained by time analysis of the feedback signal to the frequency-locked CSO for shorter time scales where the CSO has the superior stability. This work represents the first demonstration in our laboratory of any other standard that equals or betters this hydrogen maser for all measuring times.

Ruby

Sapphire

Lead Thermal Ballast

Heater Coils

RF H-Field Intensity
from Finite Element
Calculation

Thin (0.01cm)
Stainless Steel

The figure shows a plot of Frequency − 10.393 GHz (kHz) versus Temperature (K). The y-axis ranges from 960.5 to 962.5 kHz, and the x-axis ranges from 5 to 18 K. Data points marked with filled circles are labeled "Uncompensated" and data points marked with × follow a fitted curve. Annotations on the plot read:

Tmax = 8.821 K

Curvature at Tmax
= −2.08×10⁻⁹(Hz/Hz/K²)

Fit to a/T + bT⁴

Allan Deviation vs Measuring Time (seconds)

LITS / CSO vs H-maser

LITS vs CSO

$\sigma_y(\tau)=3.0 \times 10^{-14}/\tau^{1/2}$